Reprocessing Seismic Reflection Data in Order to Provide Structural Constraints on Earthquake Source Parameters in the Wabash Valley Seismic Zone

Award Number: 1434-HQ-97-GR-03065

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Program Element: III. Understanding Earthquake Processes

Key Words: Tectonic Structures; Seismotectonics; Reflection Seismology; Source characteristics.

Investigations undertaken

We present the results of reprocessing a high-quality deep seismic reflection profile that passes to within 5 km of the epicenter of the 1968.11.9 m_{bLg}=5.5 earthquake in southern Illinois [*Langer and Bollinger*, 1991]. The 1968 event is one of the largest historic earthquakes of the so-called "Wabash Valley seismic zone", which is situated northeast of the well-known New Madrid seismic zone, and covers parts of southeastern Illinois, southwestern Indiana, and western Kentucky (Fig. 1). As pointed out by *Langer and Bollinger* [1991], the Wabash Valley seismic zone has had larger and deeper earthquakes during the 20th century than the infamous New Madrid seismic zone, which was the site of the m_b=7.1-7.4 1811-1812 earthquakes [*Nuttli*, 1979]. The 1968 event is highly significant for intraplate seismicity in a worldwide context because it was the largest 20th-century earthquake for the central North American Midcontinent, including the New Madrid seismic zone, and is typical of the seismic deformation regime for this region [*Taylor et al.*, 1989]. Our reprocessing results reveal, for the first time in the North American Midcontinent, a prominent zone of dipping reflectors in the middle crust that is closely associated with the focus of a major intraplate earthquake.

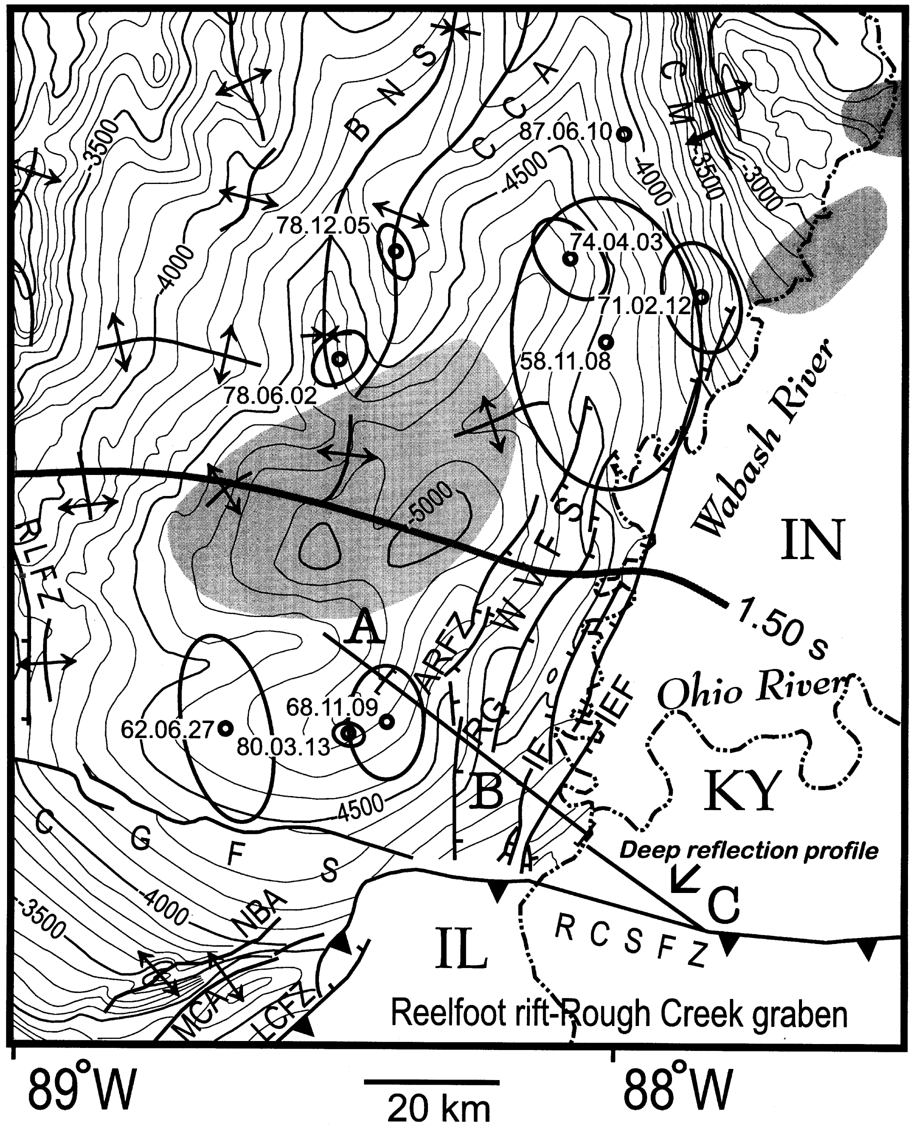

Figure 1. Map of the south-central Illinois Basin and Wabash Valley fault system (WVFS), with structure contours (feet below sea level) on the base of Upper Devonian New Albany Shale (modified from *Cluff et al*. [1981]), known structural axes [*Nelson*, 1995], and revised, instrumentally recorded epicenters (m_{bLg} 3.0) with nominal 95% confidence ellipses [*Gordon*, 1988; *Langer and Bollinger*, 1991]. Contour interval is 100 feet (~30.5 m). Thick line represents the 1.50-s traveltime contour for the base of the Centralia seismic sequence indicating its southernmost extent in the study area [*McBride and Kolata*, 1998]. Shaded areas represent interpreted buried igneous plutons based on gravity and magnetic intensity data [*Braile et al*., 1982]. RCSFZ is Rough Creek Shawneetown Fault Zone; LCFZ is Lusk Creek Fault Zone; MCA is McCormick Anticline; NBA is New Burnside Anticline; CGFS is Cottage Grove Fault System; RLFZ is Rend Lake Fault Zone; BNS is Bogata-Rinard Syncline; CCA is Clay City Anticline; CM is Charleston Monocline. ARFZ is Albion-Ridgway Fault Zone; RG is Ridgway Graben; IF is Inman Fault; IEF is Inman East Fault. Letters along profile indicate the three segments in Figure 2.

A high-quality industry seismic reflection profile was surveyed in 1988-1989 that passes 4.9 km northeast of the 1968 epicenter, based on the relocation study of *Gordon* [1988]. The 77-km long profile begins on the southeast in western Kentucky just north of the Rough Creek-Shawneetown fault zone, crosses the Wabash Valley fault system, and extends into the deeper part of the Illinois Basin (Fig. 2). The reflection survey and original contractor data processing parameters have been discussed previously by *McBride et al*. [1997] and *Potter et al*. [1997]. In these studies, using a portion of the present profile, we described the results of the original contractor processing of the 5-s record then available. The upper ~1.8 s of the record, discussed in detail previously by *Potter et al*. [1997], is a well layered sequence of nearly horizontal reflections that correspond to the well-known Paleozoic strata of the Illinois Basin (Fig. 2). As described in the previous study [*McBride et al*., 1997], the upper part of the basement (~1.8-4.0 s) consists of a broad prominent sequence, in which reflectors are subhorizontal or inclined with a strong west-dipping component, that appears beneath the Wabash Valley fault system and extends to the west beneath the Illinois Basin where it steepens and plunges deeper into the crust just over the 1968 hypocenter [*McBride et al*., 1997]. Nearby and regional drilling penetrated granitic lithologies, taken to be part of the eastern granite-rhyolite province [*Potter et al*., 1997]. These drill holes suggest that the shallow basement reflectivity may be related to the rocks of this province [*McBride and Kolata*, 1998]; however, the one drill hole along the line (Fig. 2) penetrates an apparent anomalous basement upwarp possibly associated with an igneous intrusion or other basement structure [*Potter et al*., 1997]. Therefore it is questionable how representative the scattered basement penetrations are of the shallow basement reflectivity in general beneath the Illinois Basin (see also *McBride and Kolata* [1998]).

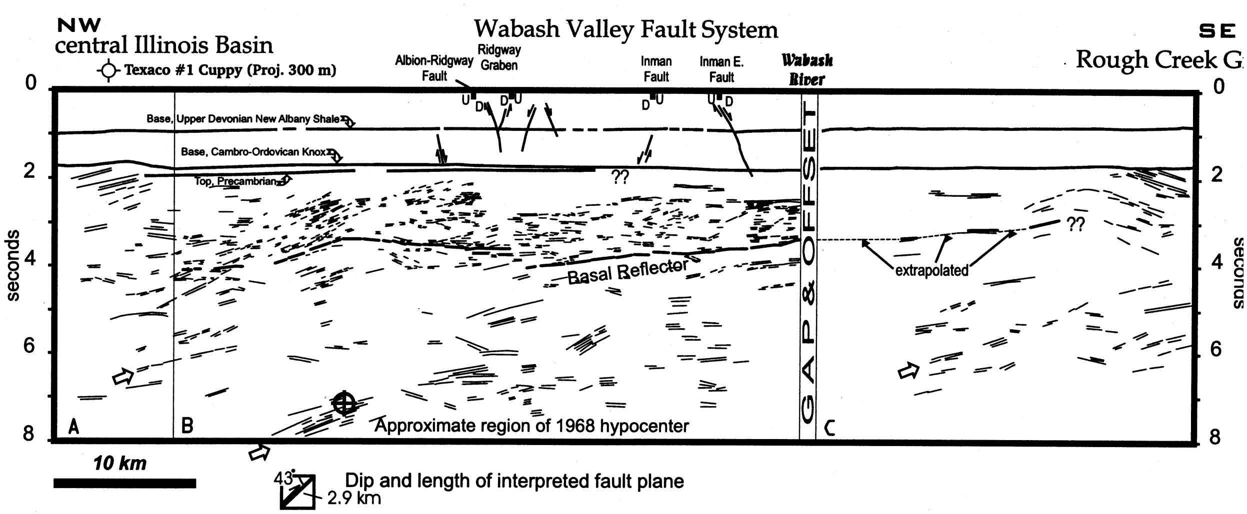

Figure 2. Line drawing interpretation of migrated seismic profile (see Figure 1 for location). Data above 5 s were processed by contractor [*McBride et al*., 1997]; below 5 s, data were reprocessed with a variable (4.5-6.0 km/s) velocity phase-shift migration. "Basal Reflector" marks the bottom of the shallow basement sequence identified originally. Three arrows show the three sets of west-dipping reflections. Small box shows apparent dip of west-dipping nodal plane for the 1968 event (interpreted as the fault plane) and its modeled rupture length. No vertical exaggeration for 6.2 km/s. Position of m_b=5.5 1968 hypocenter is shown [*Gordon*, 1988]. Depth uncertainty is ±5.4 km or ~5.4-8.9 s based on *Gordon's* [1988] estimate (but see text for alternative estimates). Mechanism from *Stauder and Nuttli* [1970]. Stratigraphic identifications from *McBride et al*. [1997].

The original shot-record data were reprocessed to include the full recorded 8 s and to enhance any images of deep crustal structure. As part of the present study, new profile segments were added to northwest and southeast of the original central profile (A and C, respectively, Fig. 2). Because the present study is focused primarily on crustal structure at or below 15 km depth, the data processing parameters were oriented toward enhancing lower frequency signal. The most important departures from the original processing strategy were (1) subsampling to 8 ms, (2) using a frequency filter (Ormsby) that included 10 Hz and higher signal, and (3) applying migrations with a range of constant velocities (3.0 to 6.5 km s^{-1}).

Finite difference, frequency-wavenumber, and phase-shift migrations were applied to the stacked sections using various constant velocities. The optimum migration was the phase-shift method (10-80 Hz; for all dip angles) using constant velocities of 4.5-6.0 km s^{-1}. A constant velocity is appropriate since we aimed the reprocessing at the post-2-s record and have no information on local crustal velocity variations. The upper, sedimentary portion of the sections has been previously migrated with a variable velocity function by the contractor. Several migration trials were performed in order to avoid overmigration artifacts and to determine which apparently linear events might be high-velocity and/or deep diffractions. On the interpretive line drawing (Fig. 2), we "filtered out" any suspicious events (e.g., residual diffractions and remaining multiple reflections). The resulting new image maximizes the expression of deep Precambrian crustal reflectors while minimizing that of the Paleozoic Illinois Basin sedimentary section. Time-to-depth conversions were carried out using information from nearby drill hole data and extrapolated from seismic refraction-based models of the crust for the northern Mississippi Embayment [*Ginzburg et al*., 1983].

Results

The results of our reprocessing not only extend the previously imaged west-dipping reflector sequence over the 1968 hypocenter deeper within the 5-s record, but also reveal a broad series of deeper west-dipping reflections, which appear as three widely spaced shingled sets (Fig. 2). The reflections within the middle crust are parallel to and appear to be a deep continuation of the shallow west-dipping basement reflections. The middle crustal reflections on profile B are situated beneath a pronounced fold or bend in the base of the shallow basement sequence. On profile C the deep west-dipping reflection series projects upward to beneath the core of a prominent antiformal reflection pattern near the northern margin of the Rough Creek-Shawneetown fault zone (Fig. 2). Elsewhere, the deeper dipping reflections seem to have no relation to the faults of the Wabash Valley fault system nor to offsets in the shallow basement sequence (e.g., on the middle of profile B).

The most prominent of the deep west-dipping reflections begins at 7.1 s on profile B and continues to the bottom of the new 8-s record, where it is abruptly cut off. The brightest and most coherent dipping reflections, within the lower part of profile B, correspond exactly to the position of the hypocenter as projected 4.9 km from the southwest, perpendicular to the line of the profile. Using the estimated depth of 21.2± 5.4 km [*Gordon*, 1988] (or 5.4-8.9 s, equivalent traveltime), the hypocenter plots near the upper surface of the 0.8-s thick band of brightest reflections (or 2.5-km thick using 6.2 km s^{-1} as a conversion velocity). *Herrmann's* [1979] depth estimate of 22± 2 km more precisely places the hypocenter within the center of this band. Since the local seismograph network was not installed until 1978 [*Gordon*, 1988], there is some inaccuracy in the epicenter location for the 1968 event (see confidence interval ellipse in Fig. 1). After the 1978 installation, three better located events (1978.06.02, 1978.12.05, 1980.03.13) in the study area occurred with focal depths in the 20-25 km depth range [*Gordon*, 1988]. The most accurately located of these is the 1980 event with a computed focal depth of 20.3± 1.8 km and m_{bLg}=3.0 [*Gordon*, 1988; *Langer and Bollinger*, 1991]. The epicenter is within a few kilometers of that of the 1968 event and the two hypocenter depths are almost indistinguishable. The close three-dimensional proximity of the two earthquakes in the Wabash Valley seismic zone may suggest a recurrent zone of stress release. Although the 1968 earthquake focal mechanism solution is clearly a reverse fault, the original interpretation by *Stauder and Nuttli* [1970], that the west-dipping nodal plane is the fault, was based on the assumption that the westernmost normal faults of the Wabash Valley fault system are upthrown to the west. However, it has been previously argued [*McBride et al*., 1997] that no connection exists between these shallow, mostly sedimentary normal faults and the hypocenter. Nevertheless, because of the close association of the hypocenter and the west-dipping reflector zone, we propose that the fault plane is indeed the west-dipping nodal plane, which dips 45° (or 43° apparent dip on the plane of the reflection profile).

Our new reprocessing results reveal for the first time in the North American Midcontinent a very close spatial relation between a prominent dipping reflector zone in the crust and an earthquake focus. A thrust fault interpretation (Fig. 3) for the west-dipping basement reflectors in Figure 2 is suggested by their appearance beneath lower Paleozoic and Precambrian antiformal structures (profiles A and C) or beneath abrupt offsets in the shallow basement sequence (profile B). A similar interpretation was put forward for shallower earthquakes beneath the Appalachian Piedmont just east of the Blue Ridge thrust front in the central Virginia seismic zone projected onto the plane of a regional deep seismic reflection profile [*Çoruh et al.*, 1988]. The appearance of a bright, coherent reflector associated with the 1968 hypocenter is all the more striking in view of the lack of any such reflector on the hundreds of kilometers of reflection profiles across the New Madrid seismic zone including the COCORP deep seismic profile [*Nelson and Zhang*, 1991]. The implications from our study for the deep seismogenic source in the central Midcontinent are that at least some of the larger earthquakes are governed by a pre-existing, west-dipping fabric of compressional structures that penetrates the upper, middle, and possibly lower crust. It is intriguing that the hypocenter-defined west-dipping thrust (~23º- ~32º) beneath the transverse segment of the New Madrid seismic zone is analogous to the strike and dip of the structure beneath the 1968 epicenter. Additional deep seismic reflection profiling is urgently needed in order to understand the 3-D structure of the seismogenic source in southern Illinois and vicinity and its link to the New Madrid seismic zone.

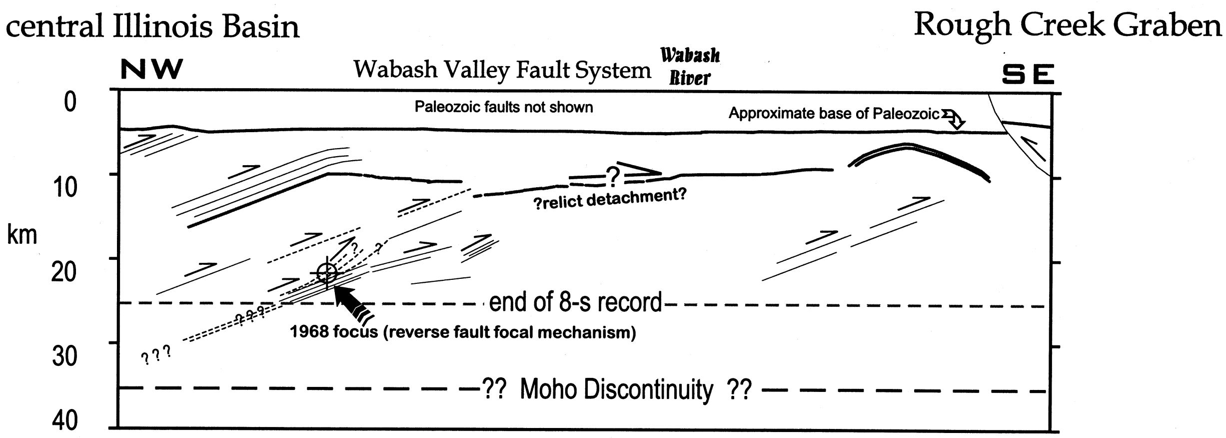

Figure 3. Interpretive model corresponding to area of Figure 2. Dashed lines are speculative. "Relict detachment" is "Basal Reflector" in Figure 2. Rough Creek graben interpretation is from *Kolata and Nelson* [1997] and Moho discontinuity is from *Allenby and Schnetzler* [1983].

REFERENCES CITED

Allenby, R. J., and Schnetzler, C. C., United States crustal thickness, Tectonophysics, 93, 13-31, 1983.

Braile, L. W., Hinze, W. J., Keller, G. R., and Lidiak, E. G., 1982. An ancient rift complex and its relation to contemporary seismicity in the New Madrid seismic zone. Tect., 1: 225-227.

Cluff, R.M., Reinbold, M.L., and Lineback, J.A., 1981. The New Albany Shale Group of Illinois. Ill. St. Geol. Surv., Cir. 518, 83 pp.

Çoruh, C., G. A. Bollinger, and J. K. Costain, Seismogenic structures in the central Virginia seismic zone. *Geol.,* 16, 748-751, 1988.

Ginzburg, A., Mooney, W. D., Walter, A. W., Lutter, W. J., and Healy, J. H., 1983, Deep structure of northern Mississippi Embayment: AAPG Bulletin, v. 67, p. 2031-2046.

Gordon, D. W., 1988, Revised instrumental hypocenters and correlation of earthquake locations and tectonics in the Central United States: U. S. Geological Survey Professional Paper 1364, 69 p.

Herrmann, R. B., 1979, Surface wave focal mechanisms for eastern North America earthquakes with tectonic implications, Journal of Geophysical Research B, v. 84, p. 3543-3552.

Kolata, D. R. and Nelson, W. J., 1997, Role of the Reelfoot Rift/ Rough Creek Graben in the evolution of the Illinois Basin, *in* Ojakangas, R. W., Dickas, A. B., and Green, J. C., eds., Middle Proterozoic to Cambrian rifting, central North America: Geological Society of America Special Paper 312, p. 287-298.

Langer, C. J. and Bollinger, G. A., 1991, The southeastern Illinois earthquake of 10 June 1987: the later aftershocks: Bulletin of the Seismological Society of America, v. 81, p. 423-445.

McBride, J. H., Sargent, M. L., and Potter, C. J., 1997, Investigating possible earthquake-related structure beneath the southern Illinois Basin from seismic reflection: Seismological Research Letters, v. 68, p. 641-649.

McBride, J. H. and Kolata, D. R., 1998, The upper crust beneath the central Illinois Basin, USA. Geological Society of America Bulletin 110, in press.

Nelson, K. D. and Zhang, J., A COCORP deep reflection profile across the buried Reelfoot Rift, south-central United States, Tectonophysics, 197, 271-293, 1991.

Nelson, W. J., 1995, Structural Features in Illinois: Illinois State Geological Survey Bulletin 100, 144 p.

Nuttli, O. W., 1979, Seismicity of the central United States: *in* Hatheway, A. W. and McClure, Jr., C. R., eds., Geology in the Siting of Nuclear Power Plants, Geological Society of America, Reviews in Engineering Geology, V. IV, p. 67-93.

Potter, C. J., Drahovzal, J. A., Sargent, M. L., and McBride, J. H., 1997, Proterozoic structure, Cambrian rifting, and younger faulting as revealed by a regional seismic reflection network in the southern Illinois basin: Seismological Research Letters, v. 68, p 537-552.

Stauder, W. and Nuttli, O. W., 1970, Seismic studies: south central Illinois earthquake of November 9, 1968: Bulletin of the Seismological Society of America, v. 60, p. 973-981.

Taylor, K. B., Herrmann, R. B., Hamburger, M. W., Pavlis, G. L., Johnston, A., Langer, C., and Lam, C., 1989, The southeastern Illinois earthquake of 10 June 1987: Seismological Research Letters, v. 60, p. 101-110.

Non-technical Summary

For the first time in the USA Midcontinent, an earthquake hypocenter (1968.11.09 m_{bLg}=5.5) can be directly associated with dipping high-amplitude mid-crustal reflections, interpreted as compressional tectonic structures possibly of Grenville age. These deep reflections, centered around a depth of 21 km, are part of a major zone of west-dipping reflectors within the upper and middle crust situated beneath the Wabash Valley Fault System in southern Illinois. The focal mechanism solution (moderately dipping reverse fault, interpreted west dip) of the earthquake is consistent with the observed reflectors. The results of our study imply that the deep seismogenic source in the central Midcontinent just north of the New Madrid seismic zone consists, at least in part, of a pre-existing west-dipping fabric of blind thrust and other compressional structure that penetrates much of the crust.

Reports published

McBride, J. H. (1998). Understanding the tectonic reactivation of structures in the Precambrian crust beneath the Illinois basin (USA) from seismic reflection profiles, International Conference on Precambrian and Craton Tectonics, Abstracts, International Conference on Precambrian and Craton Tectonics, 14th International Conference on Basement Tectonics, Ouro Preto, MG, Brazil June, 1-5, 1998, Centro de Editoração Eletrônica – CEEL Departmento de Geologia – Escola de Minas – UFOP, p. 131-132.

McBride, J. H. and D. R. Kolata (1998). Understanding the seismogenic source beneath the southern Illinois basin from seismic reflection profiles (Abstract), American Geophysical Union, Spring Meeting.

No seismic data are publicly available.